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ECONOMIC AND PERFORMANCE COMPARISONS OF SALTY AND SALTLESS SOLAR PONDS

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ECONOMIC AND PERFORMANCE COMPARISONS OF SALTY AND SALTLESS SOLAR PONDS

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ABSTRACT

The optimum solar pond design is site-dependent and application-dependent. Foremost of the design decisions is the choice of a salty (nonconvecting) pond or a saltless (convecting) pond. The decision variables are: local availability and cost of salt, type of salt available and its properties, and possible environmental factors such as the effects of salt runoff and the existence of ground water.

The availability of salt is an important factor in determining the economics of salty ponds. For example, sodium sulfate is a potentially low-cost substitute for sodium chloride, and is expected to be in plentiful and widely distributed supply in the near future as a waste product of flue gas desulfurization at coal-fired utility plants. This paper discusses the potential supply of such salts and estimates the break-point in net cost of salt at which a convecting pond becomes economically competitive with the salty pond.

THE SALTY SOLAR POND has been analyzed and tested in Israel (1*) and the United States (2,3). It has been shown to be a technically viable and economically advantageous method of producing thermal energy and storing it for long intervals.

The economics of the salty solar pond depend heavily on the local availability and price of salt. In many parts of the world, such as near the Dead Sea in Israel and near the Great Salt Lake in Utah, salt is available for virtually nothing. In other locales the price is quite significant. Since something on the order of one-half to several tons of salt are required per square metre of salty pond, the price of the salt can be the dominant portion of the price of the pond.

Where salt is expensive, a saltless solar pond may be more economical than a salty pond. The economics of the saltless pond, though not quite as attractive as those of the salty pond when salt is free or inexpensive, are still more favorable than the economics of other low-temperature solar collection techniques. The saltless pond is also attractive because it does not present the environmental hazard of salt runoff.

THE SALTY SOLAR POND

The salty solar pond uses dissolved salt to establish a concentration gradient. The salinity varies from near zero at the surface to a high level at a metre or two depth. This concentration gradient, by preventing vertical convection within the pond, enables the lower depths of the pond to retain absorbed solar heat which would otherwise be lost from the surface to the ambient air. Many salts can be used, but the most common that have been used in solar ponds are sodium chloride and magnesium chloride. Desirable properties for these salts are increasing solubility in water with increasing temperature and high transparency to solar radiation in water solution. Sodium sulfate, because it is a byproduct of flue gas scrubbing, is an attractive candidate. In general, it is more important that the salt be readily available and inexpensive than that it have optimal physical properties.

There is usually a "storage layer" near the bottom of the salty pond in which the salt concentration does not vary and where vertical convection takes place. Above this is the "nonconvective layer" of about 1 or 1-1/2 m in thickness. This nonconvecting layer provides excellent insulation for the storage layer, at the same time transmitting about 25% of the solar radiation and storing some of the energy absorbed.

LOW COST SALTS FOR SOLAR PONDS

The costs of salts for a solar pond represent a sizable fraction of the total initial investment. Depending upon the design details and the proximity to a source of salt, a typical NaCl salt pond may require 30% to 60% of the initial investment for the initial charge of NaCl (4,5). Therefore, the identification of suitable, low cost alternative salts could strongly affect the overall economic favorability of a salt pond.

A suitable salt must meet several criteria:

- it must be adequately soluble (with a solubility that increases with temperature;
- its solution must be adequately transparent to solar radiation;
- it must be widely available, so that its transportation costs do not offset the advantages of its low purchase costs; and
- it must be environmentally benign.

The amount of salt required and its necessary solubility and optical characteristics cannot be established theoretically because the understanding of stability in a stratified pond is not very well developed (6). However, certain sufficient conditions for pond stability can be inferred by analogy with successful NaCl ponds, and the overall thermal performance of a salty pond can be simulated by computer modeling when the solubility and optical properties of the alternative salt are known.

A typical NaCl pond has a solution concentration ranging from nearly zero at the surface to a maximum of 17 weight percent in the storage layer. This corresponds to a density gradient of only about 0.05 g cm^{-3} per metre depth. An alternative salt having a similar or lower diffusivity and which can provide a similar density gradient at operating temperatures should also produce a stable stratification. Fig. 1 shows the solubility of some candidate salts. In all cases, the diffusivities of the alternative salts are lower than that of NaCl and the temperature dependence of solubility is greater. Therefore, a concentration sufficient to produce a density gradient of 0.05 g cm^{-3} per metre depth in a typical operating temperature gradient ($\approx 20°C\ m^{-1}$) should provide as great or greater pond stability as would the NaCl salt.

Table 1 summarizes some properties of the candidate salts. Costs are only approximate since they vary substantially with location and time because of transportation costs; however, it is clear that only those salts that can be obtained as "waste" products

*Numbers in parentheses designate references at end of paper.

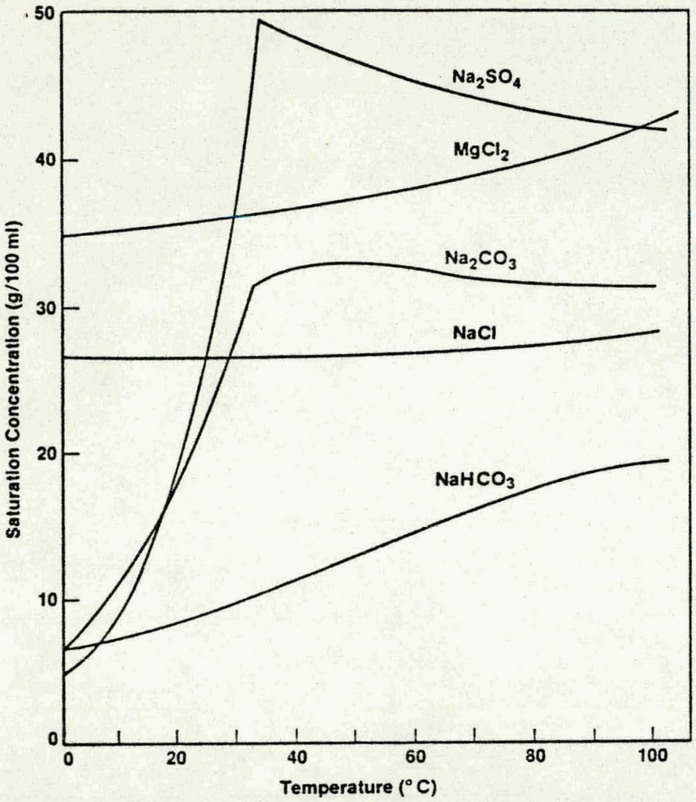

Fig. 1. - Solubility of candidate salts for solar ponds (11)

offer substantial economic advantage. The magnesium chloride "bitterns" are available from plants which refine NaCl, and these sites are numerous (Fig. 2). Sodium sulfate, however, has the potential for much more widespread availability in the next few years as a waste product from flue gas desulfurization at coal-fired power plants.

Enforcement of existing EPA air quality standards will require all new coal-fired power plants and most gas- and oil-fired power plants which will be converted to coal (as required by the National Energy Act) to have some flue gas desulfurization. Several different desulfurization processes are under development by industry and evaluation by EPRI (7); two of the most promising use Na_2CO_3 and/or $NaHCO_3$ and produce Na_2SO_4 as a flue gas desulfurization (FGD) waste product. These processes are being developed by joint ventures of Joy Industrial Equipment Company with Niro Atomizer Company (8) and Wheelabrator-Frye, Inc., with Rockwell International (9).

The quantities of FGD waste produced by a plant are enormous. A typical 500 MWe plant (burning ~ 0.2% sulfur coal) would produce approximately 250 tons of FGD waste per day. Hundreds of oil- and gas-fired power plants around the country are potential future sites for production of the FGD waste. In the southwestern United States alone the capacity of such candidate plants is greater than 76 GWe, and these plants are widely dispersed around the countryside with about 50% in rural areas near potential solar pond sites. Thus FGD waste salt may meet cost and availability criteria in the future.

Preliminary measurements at SERI indicate that the FGD waste salt's optical properties may also be acceptable although, because of impurities, the FGD salt solutions are not as transparent as fresh NaCl

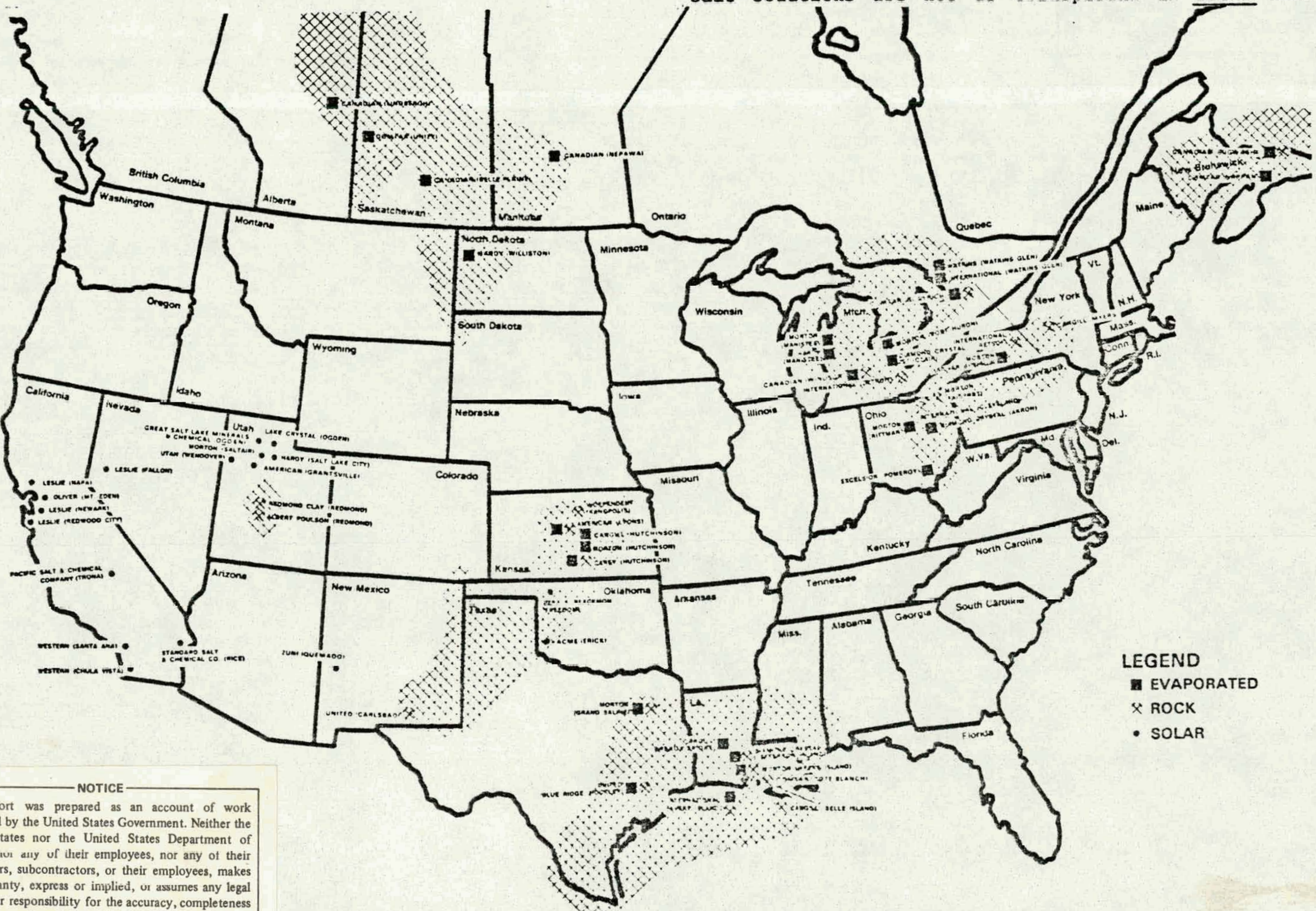

Fig. 2. - Salt production sites in the U.S. and Canada (14)

Table 1 - Properties of Candidate Salts

Salt	Formula	Source	Cost ($/10^{3}kg)	Comments
Sodium chloride	$NaCl$	(see Fig. 2)	20	
Sodium carbonate	$Na_2CO_3 \cdot H_2O$	synthetic (Solvay Process)	96	East coast price
		as Trona (Green River, Wy.)	61	Wyoming price
		as Trona (Green River, Wy.)	70	California price
Sodium Bicarbonate	$NaHCO_3$	Nahcolite (Piceance Creek Basin, Wy.)	(~35)*	Byproduct of oil shale mining (not yet in production)
Sodium sulfate	Na_2SO_4	"salt cake"	47	East coast price
		"salt cake"	45	West coast price
		as Flue Gas Desulfurization waste	(~0)*	Price depends on proximity of other markets
Magnesium chloride	M_gCl_2	salt plants (see Fig. 2)	140	99% pure, hydrated salt
		as bitterns (see Fig. 2)	(~2)*	Waste product also containing other salts (not normally sold).

*Estimated prices

solutions. Fig. 3 shows the measured optical extinction coefficient of a FGD salt in solution and a comparison of the solar absorption in a FGD waste salt pond (calculated) with a new NaCl pond (measured). The actual optical clarity of an operating NaCl pond is much poorer, but quantitative data are not available. The FGD salt solution appears to meet the requirements for optical clarity but may not perform as well as NaCl. Continuing experiments at SERI will resolve these questions.

The environmental acceptability of FGD salts remains a moot question. The Resource Conservation and Recovery Act of 1976 requires the EPA to identify hazardous wastes. Fly ash and flue gas scrubber sludges may be so designated (10). If so, then the FGD salt may require some purification before it can be used in solar ponds. How this purification might affect availability, cost, and performance remains to be determined.

THE SALTLESS SOLAR POND

The saltless solar pond is a simple idea, as yet virtually untried. The saltless solar pond, having no thick, nonconvecting layer to insulate it from the ambient air, must have glazings over the top instead. In addition, it should have extra insulation placed over the top at night and during periods of low insolation.

Because the saltless pond has less effective insulation from the ambient air than does the salty pond, it loses more heat. At the same time, because the transmissivity of its surface glazings is higher than that of the nonconvecting insulating layer in the salty pond, the saltless pond receives more insolation. The net effect is that the saltless pond is more sensitive than the salty pond to fluctuations in ambient temperature and insolation. Thus, a saltless pond with the same thermal mass as a salty pond will experience wider variations in storage temperature. If these temperature fluctuations are to be controlled, the saltless pond must have more thermal mass than the salty pond; i.e., it must be made deeper.

The insulation added at night and during periods of low insolation can be applied to the saltless pond in a variety of ways. The pond surface can be permanently insulated with water circulated to collectors during periods of sufficient solar radiation. Insulation can be spread manually over the top of the pond. Another idea is to have a "lid" propped above the pond, with a reflector on its underside to reflect additional radiation into the pond; the lid would be lowered to cap the pond whenever insolation is insufficient. One promising suggestion is to use liquid foam insulation. This material, which has been used effectively for night insulation in greenhouses, can be sprayed in the evening and simply allowed to collapse and run off in the morning.

The saltless pond is convecting, and therefore the temperature of the water is nearly the same at the surface and at the bottom. (Stratification is a possibility under some circumstances which would need to be avoided.) Hence the potential for surface losses and for "edge losses" through the surrounding ground is greater than in the salty pond. Edge losses in the saltless pond may be particularly significant nearer the pond surface, where there is less distance for the heat to travel from the pond edge to the ground surface. To retard these edge losses it may be effective to "bury" the pond slightly—that is, to fill the pond to a level somewhat below the surface of the earth.*

*The saltless solar pond discussed here is still conceptual and has not been tested adequately. It should not be confused with the shallow solar pond proposed and tested by Lawrence Livermore Laboratories (15). The Lawrence Livermore ponds are very shallow (about 10 cm) water layers encased in plastic bags. The water must be pumped to separate storage tanks at times of low insolation. The economic attractiveness of these ponds is marred by the high cost of plumbing and separate storage. The shallow solar pond is effective mainly for summer peaking loads.

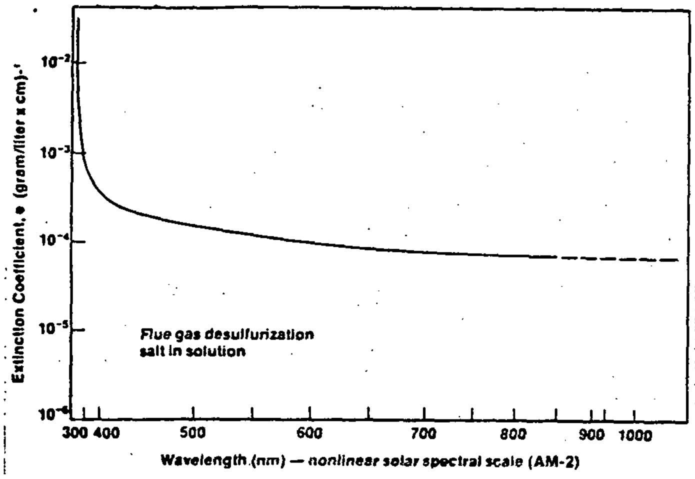

Fig. 3a. - Optical absorbance of sodium sulfate flue gas desulfurization (FGD) salt in solution

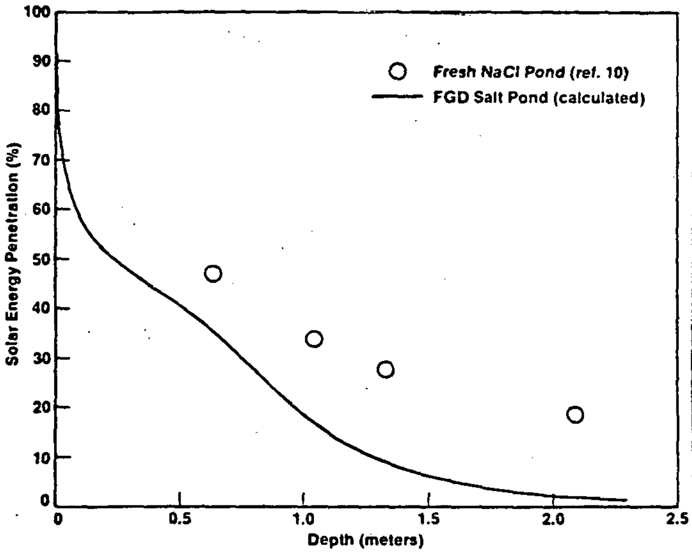

Fig. 3b. - Absorption versus depth in a typical solar (NaCl) pond and the calculated absorption in a FGD salt pond with similar salt gradient (13)

PERFORMANCE COMPARISON

A computer simulation was run of a hypothetical salty solar pond at Barstow, Calif. Employing a finite element model of the pond (16), the simulation took into account edge losses and ground storage as well as losses through the surface, losses to the ground, and pond storage.

The pond was assumed to be 30 m in diameter, roughly the size that could be used to heat a small group of houses. The pond was assumed to have a storage layer 1 m in depth, a nonconvecting layer 1.5 m in thickness, and a surface convecting layer 0.3 m thick. (The surface convecting layer is caused by wind turbulence and evaporation and cannot be avoided.) No insulation around the pond was assumed except that provided by the ground itself.

It was further assumed that a constant load of 62,832 W (50 W/m^2 of pond surface area) was extracted from the pond.

The simulation showed that the average annual temperature of the pond's storage layer would be 61°C. It would reach a maximum of 81°C about mid-August and a minimum of 41°C in mid-February.

Next, a saltless solar pond was simulated at the same location. The saltless pond was assumed to be convecting with the same temperature maintained throughout. It was assumed to have glazings over the top with a heat loss coefficient of 3 W/m^2°C and additional night insulation resulting in a nighttime heat loss coefficient of 1 W/m^2°C. Therefore the surface heat loss coefficient averaged about 2 W/m^2°C.

Transmissivity of the surface glazing to solar radiation was assumed to be 0.65.

By an iterative modeling process, a saltless solar pond was found which would have nearly the same temperature profile, under the same 50 W/m^2 constant load, as the salty pond. The saltless pond would be 30 m in diameter and would have only ground insulation--like the salty pond--but would be 10 m deep, much deeper than the salty pond. As noted, the additional depth--i.e., the additional thermal mass--is required to even out the temperature fluctuations in the saltless pond.

A computer simulation run on the saltless pond showed that its average temperature would be 60°C. Its maximum temperature, reached in August, would be 80°C and its minimum temperature, in mid-February, would be 40°C. Thus its temperature profile throughout the year would be much like that of the salty pond.

Fig. 4 shows the temperature profiles of the two ponds.

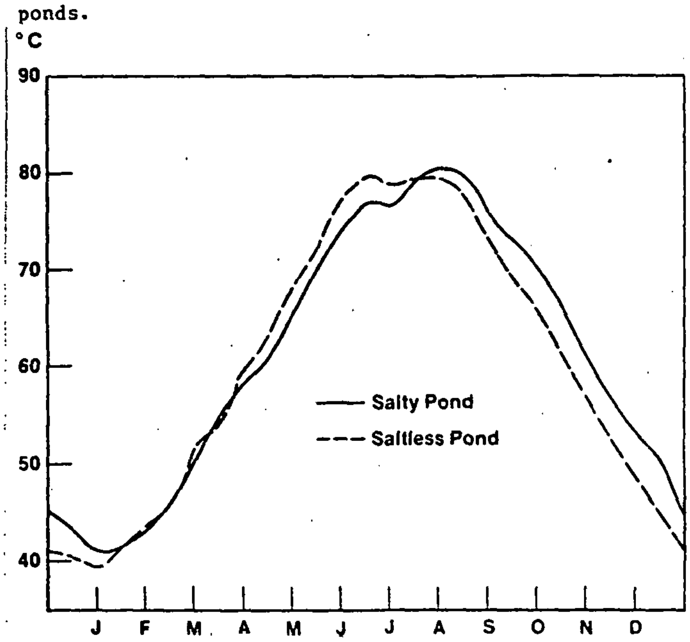

Fig. 4. - Annual temperature profiles for salty and saltless solar ponds at Barstow, Calif.

ECONOMIC COMPARISON

At the present stage of their development, solar pond costs can be only roughly estimated. These estimates will serve, however, to suggest economic comparisons between the salty and saltless ponds.

Capital expenses for the salty solar pond include excavation expense, the cost of a blackened liner for the bottom of the pond, and the cost of the salt.

The salty pond is 30 m in diameter and 2.8 m deep, so that at an excavation cost of \$2/m^3, the total excavation cost would be \$4000, or about \$5.60/m^2 of pond surface area. The liner for the bottom of the pond must be a durable material like Hypalon®, at a cost of \$10/m^2 or about \$8,000 for the entire pond (including sides).

The salty pond used in the simulations would require about 1.1 tons of salt per square metre of pond surface area. The cost of salt varies widely with proximity to the supply and may be treated as a variable in economic comparisons with the saltless pond.

Capital expenses for the saltless solar pond include excavation expense, the cost of the liner, the cost of the surface structure and glazings, and the cost for night insulation.

The saltless pond which yielded approximately the same output as the salty pond was 10 m deep. At a cost of $\$2/m^3$ the excavation expense is about \$14,000 or $\$20/m^2$ of pond surface area--$\$14.40/m^2$ more than the salty pond. However, the cost of the liner could be reduced to about $\$2/m^2$ due to the much reduced requirement for retardation of leakage. For the entire pond, the liner cost would be about \$1,600.

The cost of the surface structure and glazings depends upon the means of implementation. One possible scheme is to have a lattice structure that would be placed over the top of the pond. To this structure would be fastened sections of double-layered plastic film glazing, inflated by air at low pressure. For this design a conservative cost of $\$10/m^2$ is assumed.

If liquid foam insulation were used for night insulation, it could be sprayed into the space between the inflated plastic glazings. The cost of the liquid foam generating equipment averages less than $\$1/m^2$.

Table 2 summarizes rough costs for the salty and the saltless pond.

At a salt cost of $\$16.40/m^2$ pond surface area the cost for the salty pond equals that of the saltless pond. Since 1.1 tons of salt are required for each square metre of pond surface area, the break-even price for salt is \$14.90 per ton. At a cost of salt lower than this, the salty pond is more economical. At a cost of salt higher than this, the saltless pond is more economical. For the $\$33.30/m^2$ cost of the saltless pond, the capital cost for energy at the 50 W/m^2 extraction rate is $\$666/kW_{thermal}$.

There has been insufficient working experience with solar ponds to provide a good estimate of operation and maintenance costs. With the salty pond, there is a requirement for frequent maintenance to preserve the salt concentration gradient and to maintain water clarity. There is no reason to expect higher operation and maintenance costs with the saltless pond than with the salty pond. In fact, there is reason to expect these costs to be lower with the saltless pond since it is covered and has no salt gradient to maintain.

SUMMARY AND CONCLUSION

The solar pond is an economical way of producing low temperature thermal energy. If the cost of salt at the pond site is more than \$15 per ton, a saltless pond design may be more economical than a salty pond. The saltless pond has the further advantage of posing no environmental hazard whereas salt runoff from the salty pond may be environmentally unacceptable in some circumstances.

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Table 2 - Estimated Costs for Salty and Saltless Ponds

	Salty Pond (700 m^2 X 2.8 m)		Saltless Pond (700 m^2 X 10 m)	
Pond Component	Total Cost (\$)	Cost/m^2 (\$/m^2)	Total Cost (\$)	Cost/m^2 (\$/m^2)
Excavation	4,000	5.60	14,000	20.00
Liner	8,000	11.30	1,600	2.30
Glazings			7,000	10.00
Night Insulation			700	1.00
Salt		x		
Total/m^2		\$16.90 + x		\$33.30

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